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Aberrations of emmetropic subjects at different ages

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Abstract

We made on-axis aberrations and horizontal peripheral refraction measurements of emmetropic subjects (spherical equivalent -0.88 D to +0.75 D) aged between 19 and 70 years. We found smaller changes in on-axis aberrations with age than has previously been reported, possibly because of the small refractive error range of our subject group. Higher order root-mean-squared aberrations increased by 26% across the age range (5 mm pupils), with significant age related changes in 4th- and 6th-order aberrations. The only aberration co-efficient to change significantly was horizontal coma co-efficient C(3, 1). Several aberration co-efficients were significantly different from zero across the group of subjects. The only changes in peripheral refraction with increase in age were shifts in the turning points of the spherical equivalent and horizontal/vertical astigmatism towards less temporal visual field angles.

Keywords: Aberrations, Ageing, Astigmatism, Peripheral refraction

1. Introduction

Age-related changes take place in the eye's optical parameters, particularly in the lens. The anterior corneal radius of curvature appears to decreases with age (Hayashi, Hayashi & Hayashi, 1995). The central thickness of the unaccommodated lens increases, accompanied by decreases in anterior chamber depth (Dubbelman, Van der Heijde & Weeber, 2001; Koretz, Kaufman, Neider & Goeckner, 1989). The radii of curvature of the surfaces of the unaccommodated lens decrease with age, particularly for the anterior surface (Brown, 1974; Dubbelman & Van der Heijde, 2001). The lens gradient index changes with age, with recent studies indicating that while the higher central and lower edge indices are unaffected, the rate of change between them alters with a wider central plateau followed by a more rapid decrease in refractive index near the edge (Jones, Atchison, Meder & Pope, 2005; Jones, Atchison & Pope, 2007; Kasthurirangan, Markwell, Atchison & Pope, 2008).

Changes in ocular aberrations occur with age at fixed pupil sizes. Several studies have found that total higher-order aberrations increase with age throughout adulthood (Applegate, Donnelly, Marsack, Koenig & Pesudovs, 2007; Artal, Berrio, Guirao & Piers, 2002; Fujikado, Kuroda, Ninomiya, Maeda, Tano, Oshika, Hirohara & Mihashi, 2004; Kuroda, Fujikado, Ninomiya, Maeda, Hirohara & Mihashi, 2002; McLellan, Marcos & Burns, 2001), although one study has found that aberrations are a minimum in the thirties (Brunette, Bueno, Parent, Hamam & Simonet, 2003). There are changes in both anterior corneal and internal aberration contributions (Amano, Amano, Yamagami, Miyai, Miyata, Samejima & Oshika, 2004; Artal et al., 2002; Guirao, Redondo & Artal, 2000; Oshika, Klyce, Applegate & Howland, 1999; Wang, Dai, Koch & Nathoo, 2003). Spherical aberration changes, or there is a tendency for it to change, towards more positive values with increase in age (Applegate et al., 2007; Artal et al., 2002; McLellan et al., 2001; Smith, Cox, Calver & Garner, 2001).

The above studies had wide refractive error ranges and it is possible that there were interactions between age and refraction that may have influenced the results. Some studies have investigated myopia in restricted age ranges (Atchison, Schmid & Pritchard, 2006b; Buehren, Collins & Carney, 2005; Carkeet, Luo, Tong, Saw & Tan, 2002; Cheng, Bradley, Hong & Thibos, 2003; He, Sun, Held, Thorn, Sun & Gwiazda, 2002; Marcos, Moreno-Barriuso, Llorente, Navarro & Barbero, 2000; Netto, Ambrósio, Shen & Wilson, 2005; Paquin, Hamam & Simonet, 2002; Zadok, Levy, Segal, Barkana, Morad & Avni, 2005), with some of these studies finding greater aberrations in myopes than in emmetropes, although it must be pointed out that some of the studies finding the increased aberrations in myopia used correcting ophthalmic lenses which led to overestimates of aberrations in myopia (Atchison et al., 2006b). Llorente et al. (2004) found that hypermetropes had higher aberrations than myopes of a similar age distribution, but this was not found by Artal et al. (Artal, Benito & Tabernero, 2006).

Plainis and Pallikaris (2008) conducted a study of aberrations in 218 emmetropic (+0.75D to -1.25 D) male subjects aged 21-43 years. They found an age related increase in total higher order root-mean-squared (RMS) aberrations and third order RMS aberrations, but no significant changes in aberration co-efficients such as that for spherical aberration.

There have been several studies of peripheral refraction relative to refractive error (Atchison, Pritchard, White & Griffiths, 2005; Logan, Gilmartin, Wildsoet & Dunne, 2004; Love, Gilmartin & Dunne, 2000; Millodot, 1981; Mutti, Sholtz, Friedman & Zadnik, 2000; Rempt, Hoogerheide & Hoogenboom, 1971; Schmid, 2003; Seidemann, Schaeffel, Guirao, Lopez-Gil & Artal, 2002), but few relative to age (Atchison et al., 2005; Charman & Jennings, 2006; Millodot, 1981; Scialfa, Leibowitz & Gish, 1989). Nearly all the refractive error studies were concerned with the horizontal visual field and showed that emmetropes and hypermetropes usually have relative myopic shifts into the periphery, but that myopes usually have relative hypermetropic shifts into the periphery. However along the vertical visual field, relative myopic shifts into the periphery occur for both emmetropes and myopes (Atchison et al., 2005).

Previously we investigated how age affects peripheral refraction for 55 young subjects (24±4 years) and 41 older subjects (59±3 years) out to 35° eccentricity in the horizontal visual field (Atchison et al., 2005). Subjects were compared in 1D subgroups based on central spherical equivalent refractions (low hypermetropes +0.54 D to +1.51 D, emmetropes +0.50 D to –0.49 D, low myopes -0.50 D to –1.49 D, moderate myopes -1.50 D to –2.58 D). Both age groups showed relative hypermetropic shifts in the periphery as myopia increased and decreases in peripheral 90°-180° astigmatism J_{180} as myopia increased, the former supporting previous investigations. Overall, young and older subjects with similar refractive corrections had similar peripheral refraction components.

Charman and Jennings (2006) measured horizontal peripheral refraction in two subjects in the years 1977 and 2003 (26 year interval), and found an increase in relative peripheral myopia and a small increase in peripheral astigmatism accompanying the central hypermetropic shifts over this time, both of which are consistent with our study. Charman and Jennings also found greater changes in the nasal field rather than the temporal field, which is in accordance with a shift of the peak of the J_{180} astigmatism into the temporal visual field as myopia reduces (Atchison, Pritchard & Schmid, 2006a). Although it is gratifying that their longitudinal study supports our cross-sectional study results, Charman and Jennings's results must be treated with some caution because different instruments were used at the two times.

Because there has been some confounding of trends in on-axis higher order aberration by the possible influence of central refraction in previous studies, we have undertaken a large scale study of emmetropes over a 50 year range. We have also taken the opportunity to extend our age-related study of peripheral refraction for this subject group.

2. Methods

2.1 Subjects

The study followed the tenets of the Declaration of Helsinki and gained ethical approval from the Queensland University of Technology's Human Research Ethics Committee. Informed consent was obtained from each subject.

There were 106 subjects, with approximately 20 each in the age groups 18-29, 30-39, 40-49, 50-59, and 60-69 years and with similar numbers of males and females. 102 subjects were of Caucasian background. One eye was tested for each participant having spherical equivalent within the range -0.88 D to +0.75 D and with ≤ 0.50 D astigmatism as measured by subjective refraction. Subjects were excluded if they had corrected visual acuity poorer than 6/6 in the test eye, any ocular disease, previous ocular surgery, or had intraocular pressures greater than 21mm Hg in either eye. Lenses were Grade 1 or better for nuclear, cortical and posterior subcapsular cataract using lens photography and grading the ARED scale (AREDS, 2001). Right eyes were measured in 79 cases, with left eyes used only where they met the inclusion criteria and the right eye was outside refraction limits.

2.2 On-axis aberrations

Ocular aberrations were determined using a COAS Hartmann-Shack wavefront analyser (Wavefront Sciences, USA) which uses a superluminescent diode source at a central wavelength of 840nm and a 210μm pupil sampling interval. Approximately, a –0.7D correction is applied for 550nm (Ma, Atchison & Charman, 2005). Measurements were taken with a natural pupil in all but 19 cases where the natural pupil was small (< 5.0 mm), in which case the pupil was dilated with 2.5% phenylephrine. Three images were taken for each eye. Aberrations were determined for the OSA/ANSI standard (American National Standards Institute, 2004) up to 6th radial order for 5mm pupils. These were referenced to the anterior cornea. Averages of individual aberration co-efficients were determined. Signs of some left eye co-efficients were changed to make left and right eye data comparable (ANSI, 2004).

Corneal aberrations were determined with the natural pupil and the Medmont E-300 computerized video-keratoscope combined with the computer package VOL-CT V6.3 (Sarver & Associates) which performs a raytrace into the anterior cornea from infinity to determine aberrations. As for the wave aberration data, signs of some left eye co-efficients were changed. The instrument has an “accuracy index” based on movement between consecutive frames, the accuracy of distance of the fixation source from the eye, and accuracy of centration. We used an image for each subject for which the index was high at above 95%.The Medmont E-300 software gives the position of the pupil centre relative to the corneal vertex. Corrections were made to the corneal topography data so that the reference position was the undilated pupil centre as taken with the COAS instrument (Tabernero, Atchison & Markwell, in press). Similar corrections were made for the COAS results for dilated pupils. This is an improvement on many previous estimates where the corneal vertex was used or the cornea was referenced to the pupil centre under the conditions of use. If the eye is not cyclopleged under both aberration and corneal topography conditions, or if the measurements are not taken simultaneously as is the case for one instrument (Kelly, Mihashi & Howland, 2004), the higher illumination of the latter may lead to the pupil size being much smaller with a consequent change in pupil centre (Walsh, 1988; Wilson, Campbell & Simonet, 1992; Yang, Thompson & Burns, 2002). In an investigation of pupil centre and its effects on corneal aberrations for 62 of our subjects (Tabernero et al., in press), the mean absolute change in pupil position between topography and aberrometer conditions was 0.21±0.11 mm. Analysis showed that this had significant effects on only the comas among the higher order aberrations, but these effects were generally small at < 0.05 μm for 68% of the group and only > 0.10 μm for 4% of the group (5 mm pupils).

Contributions of internal ocular components to ocular aberrations were estimated by subtracting corneal aberration co-efficients from total aberration co-efficients.

The process of referencing data to undilated COAS pupil centres reduced the usable subjects from 106 subjects to 99 for COAS, 95 for corneal topography, and 88 for internal aberrations. Reasons for loss of subjects were that the dilated pupils with the COAS did not include 5 mm diameter around the undilated centre, undilated COAS images were not available, and poor imagery did not allow the recentring software to work properly for the COAS or Medmont instruments.

2.3 Peripheral refractions

Non-cycloplegic refractions were measured along the horizontal visual field in 5° steps out to 30° and then at 34° using a Shin-Nippon SRW5000 autorefractor for all subjects. Provided pupil size is at least 3.0 mm, pupil size will not influence measurements (Mallen, Wolffsohn, Gilmartin & Tsujimura, 2001). Pupil sizes in our study were at least 4 mm diameter, so the effective horizontal dimension was always greater than the necessary 3.0 mm. Five measurements were taken at each position, with subjects rotating their eyes to look at black cross targets along a flat wall 3.3 m away, and the alignment mire maintained in clear focus over pupil centres. For right eyes, fixation to a subject's right side corresponded to the nasal visual field. Averages of two data sets were taken.

Young subjects may have accommodated to the targets, for which there was less than 0.10 D variation in accommodation stimulus across the horizontal visual field. This was not considered a problem as peripheral refraction profiles are not affected by accommodation stimuli less than 1 D (Smith, Millodot & McBrien, 1988).

Analysis was similar to that used previously (Atchison et al., 2006a). The instrument's sphere/cylinder/axis refractions S/C x θ were converted to spherical equivalent M, 90º-180º astigmatism J_{180}, and 45-135º astigmatism J_{45} refraction components. Nasal visual field angles were given a positive sign. Considerable fluctuations were found at -15°, which corresponded to the blind spot and this was not included in analyses. Orthogonal polynomial regression on mean data showed that second-order fits were appropriate for all age groups for M and J_{180} and first-order fits were appropriate for nearly all age groups for J_{45}. Age group fits used a weighted least squares procedure where the weightings were provided by the inverse of the variances at each field angle. First-order fits were given by $y = bx + c$ and second-order fits were given by $y = a\,(x + b)^2 + c$, where x is visual field angle, y is refraction component and a, b and c are co-efficients.

Fitting co-efficients for each subject and refraction component were determined and regressed against age. Where co-efficient a was not significantly different from zero, values of b were unreliable and were excluded from regressions (21 cases for M and 1 case for J_{180}).

3. Results

3.1 On-axis aberrations

Figure 1 shows RMS ocular aberrations as a function of age. As found several times before, the third order aberrations dominate. In the midst of considerable variation which seems to be age-invariant , higher order aberrations increase with age, but this is significant only for total RMS aberrations and the 4^{th} and 5^{th} order RMS aberrations (the latter not shown). The only co-efficient to change significantly with age is the horizontal coma co-efficient C(3, 1)(Figure 2). C(4, 0) is positive for the majority of subjects, in line with previous studies, with a mean of +0.061±0.062 μm that is significantly different from zero ($p < 0.001$). The means of several other co-efficients are significantly different from zero: C(3, -3) , C(3, -1), C(3, 1), C(4, -4), C(5, -3), C(5, 1) and C(6, -4).

Figure 3 shows corneal RMS aberrations as a function of age. Higher order aberrations increase with age, but this is significant only for total RMS aberrations and the 6th order RMS aberrations (the latter not shown). No co-efficients vary significantly with age – see Figure 4 for C(3, 1) and C(4, 0). C(4, 0) is twice what it is for the overall eye with a mean of +0.123±0.039 μm. Several other co-efficients are significantly different from zero, including in the 3^{rd} and 4^{th} orders C(3, -3), C(3, -1) and C(3, 1).

Figure 5 shows internal RMS aberrations as a function of age. Total RMS aberrations do not increase significantly with age, and of the 3^{rd} to 6^{th} orders only the 6^{th} order RMS aberrations increase significantly with age (not shown). The only co-efficient to change significantly with age is the horizontal coma co-efficient C(3, 1)(Figure 6). Several co-efficients are significantly different from zero, including in the 3^{rd} and 4^{th} orders C(3, -3), C(3, -1), C(3, 1), C(4, 0) and C(4, 4).

3.2 Peripheral refractions

Equation fits for different age groups are given in Table 1. The few co-efficients found not to be significant by t-tests have asterisks. Peripheral refraction components are shown in Figures 7 to 9 for the groups. These figures show the spherical equivalent M, 90°-180° astigmatism J_{180} and 45°-135° astigmatism J_{45} as a function of visual field angle. For clarity, plots have been staggered along the vertical axis.

Figure 7 shows M as a function of visual field angle. All age groups show peripheral myopic shifts of similar shape. Peaks are in the temporal visual field but shift towards the nasal visual field as age increases. The similar shapes of the fits is supported by the non-significance of the regression of co-efficient “a” in Figure 10a, while the peak shifts significantly at a rate of +0.18 D/year with age (Figure 10b; note that the peak has the opposite sign to “b”).

Figure 8 shows J_{180} as a function of visual field angle. The pattern is the same as for M, with similar shapes at all ages (see also non-significance of regression of co-efficient “a” in Figure 10c) and with temporal visual field peaks shifting towards the nasal visual field at a rate of +0.11 D/year (opposite to that of co-efficient “b” in Figure 10d).

Figure 9 shows J_{45} as a function of visual field angle. Slopes are positive up to the 50s, but negative in the 60s group. Regression of individual subjects’ data shows no significant trend with age (regression of co-efficient “b” in Figure 10e).

Males and females have similar trends, except that the non-significant shift in the steepness of the J_{180} function with age (regression of “a” co-efficient in Figure 10c) is also not significant for males (-9.3×10^{-7} D/degree^2/yr, $p = 0.77$) but is significant for females who show decreasing astigmatism (increasing in absolute terms) into the periphery at a rate of -5.6×10^{-6} D/degree^2/yr ($p = 0.03$).

4. Discussion

It must be appreciated that this is a cross-sectional study characterising the optical nature of emmetropic eyes of different age groups. It does not take into account the changing refraction of people as a function of age (Saunders, 1981; Saunders, 1986; Slataper, 1950), and thus should not be used as a prediction of how the optics of individual eyes change as they age.

4.1. On-axis Aberrations

Several studies have found increases in aberrations with aging, most notably spherical aberration (see Introduction). While we have also found increases in RMS aberrations for 5mm, the changes are modest at about 26% between the ages of 20 years and 70 years. We did not find significant increases in spherical aberration, but found significant changes in horizontal coma. Both corneal and internal horizontal coma changed with age in the same direction, although only the latter changed significantly. We found a number of ocular aberrations to be significantly different from zero, in line with previous studies (Porter, Guirao, Cox & Williams, 2001; Thibos, Hong, Bradley & Cheng, 2002). Like these studies, spherical aberration stands out in this regard with a mean of +0.06±0.06 μm

Possible reasons for not finding the considerable age dependence of aberrations reported in previous studies are the reduced refraction range (-0.88 D to +0.75 D) and the strict inclusion criteria for the clarity of the lens. Most age-related studies have included large refraction ranges. It is likely that in the majority of cases there was a trend towards hypermetropia with increasing age in line with changes in refraction in the general population (Saunders, 1981; Saunders, 1986; Slataper, 1950). Excluding very high myopes, it is likely that aberrations are similar in myopes and emmetropes (see Introduction) despite the prediction that myopes' aberration might be higher because of the changes in conjugate points accompanying increase in axial length (Cheng et al., 2003). One of the two studies that have investigated aberrations in hypermetropia has found that hypermetropes have greater aberrations than myopes, while the other study found no differences (Artal et al., 2006; Llorente et al., 2004).

We investigated the significant changes found for the C(3, 1) co-efficient with age. Some studies have investigated aberrations as a function of the displacement of the corneal reflex with respect to the centre of the pupil (Artal et al., 2006; Tabernero, Benito, Alcon & Artal, 2007), this displacement being related to angle lambda (or kappa), the angle between the line of sight and the pupillary axis. The line of sight is the line joining the fixation point and the centre of the entrance pupil, while the pupillary axis is the line passing the centre of the pupil at the centre of curvature of the cornea (Atchison & Smith, 2000). While we do not have information about this displacement, we do have the pupil centre locations, relative to the corneal geometric centre, from aberrometer and corneal topography measurements (Tabernero, Atchison and Markwell, in press). As well as the natural pupil decreasing in size with increase in age, for the aberrometer we found 0.0024 mm/year nasal shift in the pupil centre (adjusted R^2, $t = 3.01$, $p = 0.003$). However, while the pupil shift was significantly correlated to the pupil diameter ($p = 0.02$) and the ocular aberration co-efficient C(3, 1) was marginally correlated to the pupil shift ($p = 0.06$), there were no significant correlations of ocular, corneal and internal C(3, 1) co-efficients with pupil diameter (p = 0.64, 0.64 and 0.73, respectively).

Internal coma changed significantly with age. This could be related to change in the lens such as tilt and decentration, but we are not aware that changes in these with age have been investigated.

4.2 Peripheral refraction

Our earlier study found that young and older people with similar refractive errors had similar peripheral refraction components in the horizontal visual field (Atchison et al., 2005). This study has extended these findings in the case of emmetropic subjects by including a larger range of ages. In the midst of considerable inter-individual variability which does not seem to be age-dependent (Figure 10), this study supports the earlier study by confirming the slightly myopic periphery, high J_{180} astigmatism, no significant variation in oblique astigmatism J_{45} across the visual field, and turning points in mean sphere M and J_{180} in the temporal visual field. As we noted for the previous study, this is surprising given the considerable age-related changes taking place in the eye's optics (see Introduction). Unlike the previous study, the fitting co-efficients for the mean sphere related to steepness and turning point were significant and we were able to determine a significant movement of the turning points for M and J_{180} towards the nasal visual field at rates of 0.18 degrees/yr and 0.11 degrees/yr, respectively.

In another study of peripheral refraction in myopia (Atchison et al., 2006a), we investigated the relationship between the turning point in astigmatism and both angle alpha (obtained from alignment of Purkinje images with an ophthalmophakometer) and lens tilt (obtained from magnetic resonance images). We found a significant correlation between the turning point and angle alpha but not between the turning point and lens tilt.

We do not have angle alpha data for our subjects, but we did some analyses based on pupil centre relative to the geometric corneal centre. Using the Liou and Brennan model eye (Liou & Brennan, 1997) we found that shifting the stop centre in the nasal direction, as occurs with increase in age at a rate of 0.0024 mm/year, moves the turning points for spherical equivalent M and J_{180} astigmatism by 2.3 degrees/0.1 mm and 0.25 degree/0.1mm. These results predict changes in the turning points for M and J_{180} astigmatism of 0.06 deg/year and 0.006 degree/year, respectively. While these are much smaller than the actual rates of 0.18 and 0.11 degrees/year, and are highly susceptible to changes in parameters of the model eye, the modelling suggests that there is a role for pupil centre shift with age to influence the turning points.

It is possible that small changes in retinal shape with age might contribute to changes in the turning point, but we not aware of any literature findings regarding such retinal changes.

5. Conclusion

We have found relatively small changes in on-axis aberrations and horizontal peripheral refraction with age for a group of emmetropic subjects. Increases in RMS aberrations are modest at about 26% between the ages of 20 years and 70 years for 5mm pupils. We did not find significant increases in spherical aberration, but found significant changes in horizontal coma. Our findings suggest that the greater age-related changes found in previous studies may have been influenced by the age-related changes in refraction occurring within subject populations. The changes in peripheral refraction with age were shifts in the peaks of the spherical equivalent and horizontal/vertical astigmatism towards less temporal angles.

Acknowledgement

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Tables

Table 1. Polynomial fit co-efficients for M, J_{180} and J_{45} for each age group shown in Figs. 7-9, respectively. * not significant ($p > 0.05$)

		a	*b*	*c*	R^2
M	18-29 yrs	-0.00063	+8.964	+0.090	0.87
	30-39 yrs	-0.00074	+13.404	+0.089	0.95
	40-49 yrs	-0.00091	+7.407	+0.077	0.98
	50-59yrs	-0.00084	+6.256	+0.225	0.95
	60-69 yrs	-0.00083	+0.804*	+0.217	0.89
J_{180}	18-29 yrs	-0.00099	+8.352	+0.063	0.99
	30-39 yrs	-0.00107	+8.296	+0.115	0.99
	40-49 yrs	-0.00112	+4.945	+0.032	1.00
	50-59yrs	-0.00115	+5.136	-0.036	1.00
	60-69 yrs	-0.00114	+3.631	-0.069	1.00
J_{45}	18-29 yrs	-	+0.0028	-0.049	0.02
	30-39 yrs	-	+0.0009*	-0.096	0.10
	40-49 yrs	-	+0.0010*	-0.029	0.26
	50-59 yrs	-	+0.0046	-0.068	0.51
	60-69 yrs	-	-0.0014	-0.050	0.33

Figure Captions

Figure 1. Ocular RMS aberrations as a function of age (5 mm pupils). Regression equations are: total higher order aberrations $y = +0.161 + 0.00093age$, $p = 0.05$; Third-order $y = +0.134 + 0.00072age$, $p = 0.12$ (**ns**); Fourth-order $y = +0.070 + 0.00063age$, $p = 0.04$; Fifth-order (not shown) $y = +0.022 + 0.00024age$, $p = 0.04$; Sixth-order (not shown) $y = +0.021 + 0.00009age$, $p = 0.37$ (**ns**).

Figure 2. Ocular aberration co-efficients C(3, 1) and C(4, 0) as a function of age (5 mm pupils). Regression equations are: C(3, 1) $y = +0.078 - 0.00229\text{age}$, $p < 0.001$; C(4, 0) $y = +0.044 + 0.00040age$, $p = 0.35$ (**ns**).

Figure 3. Corneal RMS aberrations as a function of age (5 mm pupils). Regression equations are: total higher order aberrations $y = +0.231 + 0.00147age$, $p = 0.03$; Third-order $y = +0.186 + 0.00131age$, $p = 0.06$ (**ns**); Fourth-order $y = +0.127 + 0.00036age$, $p = 0.15$ (**ns**); Fifth-order (not shown) $y = +0.047 + 0.00013age$, $p = 0.53$ (**ns**); Sixth-order (not shown) $y = +0.022 + 0.00033age$, $p = 0.01$.

Figure 4. Corneal aberration co-efficients C(3, 1) and C(4, 0) as a function of age (5 mm pupils). Regression equations are: C(3, 1) $y = -0.077 - 0.00095age$, $p = 0.26$; C(4, 0) $y = +0.126 - 0.00006age$, $p = 0.81$. The mean for C(4, 0) is $+0.123 \pm 0.039$ μm.

Figure 5. Internal RMS aberrations as a function of age (5 mm pupils). Regression equations are: total higher order aberrations $y = +0.230 - 0.00002age$, $p = 0.98$ (**ns**); Third-order $y = +0.194 - 0.000329age$, $p = 0.54$ (**ns**); Fourth-order $y = +0.105 + 0.00004age$, $p = 0.192$ (**ns**); Fifth-order (not shown) $y = +0.047 + 0.00024age$, $p = 0.29$ (**ns**); Sixth-order (not shown) $y = +0.031 + 0.00030age$, $p = 0.04$.

Figure 6. Internal aberration co-efficients C(3, 1) and C(4, 0) as a function of age (5 mm pupils). Regression equations are: C(3, 1) $y = +0.163 - 0.00150\text{age}$, $p = 0.05$; C(4, 0) $y = -0.089 + 0.00064age$, $p = 0.14$ (**ns**). The mean for C(4, 0) is -0.061 ± 0.063 μm.

Figure 7. Spherical equivalent M as a function of visual field angle for different age groups. Error bars indicate standard errors. Results have been offset vertically in 0.5 D steps for clarity. Curve fit co-efficients before the offsets are shown in Table 1. The results for (-)15º temporal field were not used in curve fits.

Figure 8. Mean J_{180} astigmatism as a function of visual field angle for different age groups. Other details are as for Figure 7.

Figure 9. Mean J_{45} astigmatism as a function of visual field angle for different age groups. Other details are as for Figure 7.

Figure 10. Peripheral refraction fitting co-efficients for all subjects as a function of age. a) Co-efficient "*a*" for spherical equivalent M, with $y = -0.0006 - 2.6721 \times 10^{-6} age$, $p = 0.54$ (**ns**); b) Co-efficient "*b*" for spherical equivalent M, with $y = +14.8346 - 0.1818 age$, $p = 0.006$; c) Co-efficient "*a*" for J_{180} astigmatism, with $y = -0.0010 - 3.1564 \times 10^{-6} age$, $p = 0.12$ (**ns**); d) Co-efficient "*b*" for J_{180} astigmatism, with $y = +11.3277 - 0.1114 age$, $p < 0.001$; e) Co-efficient "*b*" for J_{45} astigmatism, with $y = +0.0041 - 5.5944 \times 10^{-5} age$, $p = 0.30$ (**ns**).

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